DROPLET SIZE MEASUREMENTS FOR LIQUID STREAMS INJECTED INTO A LOW-PRESSURE CHAMBER USING A LIGHT TRANSMISSION TECHNIQUE

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THESIS

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Droplet Size Measurements for Liquid Streams Injected into a Low-Pressure Chamber using a Light Transmission Technique

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ABSTRACT

An apparatus was constructed for optical investigation of the sprays produced by liquid injection into a vacuum using various nozzle orifice sizes and driving pressures. A light transmission technique was employed to measure the mean diameter of the droplets in acetone sprays. Independent calculation of the densities of the sprays allowed the droplet sizes to be established by measuring the optical transmittance of a single spectrally pure wavelength of light through the sprays. A graph of droplet diameter, normalized for nozzle orifice diameter, vs. driving pressure was constructed. Mass and volume flow rates for the liquid injection system were calculated.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF SYMBOLS

$\mathring{A}$	Angstrom unit
α	Size number = $\frac{\pi D}{\lambda}$
C_n	Number of particles per unit volume
C_v	Volume of particles per unit volume
d_o	Injection orifice diameter
D	Droplet diameter
D_{32}	Ratio of the third moment of the size distribution function to the second moment
I	Intensity of light after it has passed through an aerosol
I_o	Initial intensity of light
K	Scattering coefficient
ℓ	Optical path length
λ	Wavelength of light
m	Refractive index of particles relative to the surrounding medium
Nr(D)	Size distribution function
P_d	Injection driving pressure
ρ	Phaseshift parameter = $2\alpha(m - 1)$
ρ_{32}	Phaseshift parameter based on the diameter D_{32}
T	Optical transmittance = I/I_o

NOTE: Mean values are denoted by a bar (-) above the symbol.

ACKNOWLEDGEMENT

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I. INTRODUCTION

Recently there has been considerable interest in the mechanisms of liquid injection and their role in the control of the rate and/or completeness of combustion. When a rocket motor is ignited at a high altitude, the combustion chamber pressure may be low enough to cause disruption of the propellant jets before impingement occurs. Such fanning of the jets will result in a serious ignition delay when hypergolic propellants are used. Hence, much work has been done [Refs. 1, 2, 15, 16] to determine how the atomization process can be modified or completely changed in character by environmental changes. Specific attention has been paid to the droplet sizes that are produced by different types of injectors under various environmental conditions [Refs. 3, 4, 6, 8].

The preponderance of droplet size analysis attempted in the past was approached via a tedious photomicrographic method. Photography offered a simple way to record a statistically valid sample of the droplets produced in a test. But since aerosol droplet sizes fluctuate in time, a method of size measurement that affords greater rapidity than a photographic method is desirable.

A theory of light scattering by small particles has been derived from Maxwell's equations for the behavior of electromagnetic waves [Refs. 12, 13, 18]. Application of the optical properties of an aerosol as a possible indicator

of droplet sizes is relevant to the development of a method appropriate to the case at hand.

Droplet size measurements using optical properties are relatively straightforward when the droplet sizes are uniform, i.e., a monodispersion. However, the present case presents a polydispersion made up of various time dependent sizes. This investigation applies a method due to Dobbins and Jizmagian [4] for interpreting the optical transmittance of a polydispersion in terms of a well-defined mean droplet diameter. This approach is unqualified with respect to droplet sizes, and can be applied to droplets, aerosols, and colloidal suspensions.

II. LIGHT TRANSMISSION THEORY

When a parallel beam of light is incident upon an aggregation of dielectric particles uniform in size and spatial distribution, the fraction of the incident energy that emerges without experiencing a deflection from the original direction of propagation is given by Dobbins and Jizmagian [5] as

$$T = \frac{I}{I_o} = \exp\left[-K(\alpha,m)\ \frac{\pi D^2}{4}\ C_n\ \ell\right] \qquad (1)$$

where

- T is the optical transmittance
- I is the intensity of the light after it has passed through the aggregation
- I_o is the initial intensity of the light
- $K(\alpha,m)$ is the scattering coefficient for dielectric particles
- α is the size number ($\alpha = \pi D/\lambda$)
- m is the refractive index of the particles relative to the surrounding medium
- D is the particle diameter
- C_n is the number concentration, or number of particles per unit volume
- ℓ is the optical path length
- λ is the wavelength of the light

In the inverse problem to the one of interest here, Equation (1) can be used to test the solution of Maxwell's

wave equations for electromagnetic waves incident on a sphere as developed by Gustav Mie [Refs. 12, 13, 17] in 1908. That is, the scattering coefficient can be calculated from the spectral transmittance of a known concentration of particles of predetermined diameter. The value of the scattering coefficient so obtained can then be compared with the theoretical value given by the Mie theory. Experiments of this kind show agreement of better than 10 per cent between experiment and theory for a broad range of $K(\alpha,m)$ [5]. Hence, it can be safely assumed that use of the Mie theory will yield valid results for the scattering coefficients of suspensions of uniform but unknown particle size and concentration.

Equation (1) has little significance in most practicle applications, however, because few dispersions are of uniform size. Dobbins and Jizmagian [5] circumvented the difficulty presented by the polydispersion by observing that a particular mean diameter is directly related to a mean scattering cross section for a variety of distribution functions, and is relatively independent of the shape of the size distribution function which is usually unknown. The development of this observation advanced by Dobbins and Jizmagian is partially reproduced here.

The extension of Equation (1) for a polydispersion results in

$$T = \exp\left[-\frac{\pi}{4} C_n \ell \int_0^{D_\infty} K(D,m)\ Nr(D)\ D^2\ dD\right] \qquad (2)$$

where Nr(D) is the particle size distribution function defined such that $\int_{D_1}^{D_2} Nr(D)dD$ is the relative probability of occurrence of particle sizes between D_1 and D_2. In this form the transmittance law still offers no prospect of a determination of unknown particle size. However, a mean scattering coefficient is defined as

$$\bar{K} \equiv \frac{\int_{o}^{D_\infty} K(D,m)\ Nr(D)\ D^2 dD}{\int_{o}^{D_\infty} Nr(D)\ D^2\ dD} \tag{3}$$

Further, the number concentration, C_n, can be eliminated in favor of volume concentration, C_v, i.e., the volume of particles per unit volume, such that for spherical particles

$$C_v = C_n \frac{\pi}{6} \int_{o}^{D_\infty} Nr(D)\ D^3 dD \tag{4}$$

Inserting Equations (3) and (4) into Equation (2), and defining a mean diameter, D_{32}, as

$$D_{32} \equiv \frac{\int_{o}^{D_\infty} Nr(D)\ D^3\ dD}{\int_{o}^{D_\infty} Nr(D)\ D^2\ dD} \tag{5}$$

the transmittance relation becomes

$$T = \exp\ [-\frac{3}{2}\ (\bar{K}/D_{32})\ C_v\ \ell] \tag{6}$$

A simple interpretation of D_{32} becomes clear by noting that the volume to surface ratio of a collection of spherical particles of uniform size is D/6. The volume to surface

ratio of a collection of C_n particles per unit volume of disperse sizes is

$$\frac{D_{32}}{6} = \frac{C_n \frac{\pi}{6} \int_0^{D_\infty} Nr(D)\ D^3\ dD}{C_n\ \pi \int_0^{D_\infty} Nr(D)\ D^2\ dD} \tag{7}$$

Thus the volume-surface mean diameter is that diameter which is exactly six times the volume to surface ratio of the polydispersion, and is the ratio of the third moment to the second moment of the size distribution function. More simply, if a polydispersion is replaced by a monodispersion possessing the same volume to surface ratio, then the diameter of the particles composing the monodispersion is equal to the D_{32} of the polydispersion.

The transmittance law as expressed by Equation (6) is sufficient to directly measure the quantity $\overline{K}/D_{32}$, the mean specific scattering cross section, if the particle volume concentration is known. Evaluating this same equation for two widely separated wavelengths of light will yield both the mean particle diameter and the concentration for parent populations for which C_n or C_v cannot be determined.

Evaluation of $\overline{K}$ is a complete investigation in itself and will only be touched upon lightly here. The mean scattering coefficient, normally given by a slowly converging series, can be approximated by

$$K = 2 - (4 \sin \rho)/\rho + 4(1 - \cos \rho)/\rho^2 \tag{8}$$

in which the phase-shift parameter is $\rho = 2\alpha(m-1)$. For $\rho >> 1$ Equation (8) gives $K = 2$, while for $\rho << 1$ it reduces to $K = \rho^2/2$. Thus, for particles much larger than the wavelength of the incident light $\bar{K}/\rho_{32} \rightarrow 2/\rho_{32}$ for $\alpha >> 1$. Where these simplifying assumptions cannot be made, values of $\bar{K}$ may be extracted from exact tabulations of the mean scattering coefficient vs. various phase-shift parameters for a large range of relative refractive indicies. Several tables of this nature are given in Refs. 9, 11, and 13.

An alternate optical approach for this investigation would have been to measure the angular distribution of scattered light to obtain information on particle size distribution. However, the prediction of scattered light intensity by Mie's theory can only be used when multiple scattering is absent. Hence, a concentration limitation is imposed that can preclude valid interpretation of light scattering measurements.

The transmittance method used in this investigation is less sensitive to the error caused by multiple scattering, because the portion of the incident light beam that does not suffer attenuation can usually be separated from scattered light (even in the presence of high particle concentration) by using a highly collimated incident beam and a receiver of correspondingly high angular resolution. The transmittance method generally requires less elaborate apparatus, specifically less sensitive detection equipment, and thus it was chosen for this investigation.

III. EXPERIMENTAL APPARATUS

A major portion of the time spent on this project was devoted to the design, procurement, and assembly of the components of the systems shown in Figures 1 and 7. A detailed description of these systems is presented herein as a means to help the reader better understand the experiment and as an aid to those who may wish to do further experimentation.

A. LIQUID INJECTION SYSTEM

The liquid injection system constructed for this study consisted of a liquid accumulator, an injector, a vacuum chamber, and pressure measuring devices. Figures 1 and 2 show, respectively, a photograph and a schematic diagram of this system.

All components of this system were connected with 3/8-inch stainless steel tubing, with the exception of the vacuum line which was common rubber vacuum hose. Junctions were sealed with Swagelok fittings. A vacuum seal was insured at the interchangeable nozzle assembly by means of a series of rubber O-rings, as shown in Figures 3 and 4. Closing and bleed valves were positioned at convenient locations throughout the system.

The liquid accumulator was pressurized by compressed nitrogen. Accurate pressurization levels were easily attained by first setting a coarse line pressure at the

nitrogen bottle pressure regulator and then adjusting the downstream Grove differential pressure regulator until the desired line pressure was indicated on the associated pressure gauge. Once a desired pressure setting had been made, the Grove regulator maintained that line pressure downstream, even after injection had begun. Injection into the vacuum chamber was initiated by a hand operated ball-valve just upstream of the nozzle assembly.

A common laboratory bell jar and baseplate formed the vacuum chamber. The bell jar had an inside diameter of 13.6 inches, an apex above the baseplate of 22.7 inches, and a volume of 2978 cubic inches. Easy evacuation of this chamber was achieved with the aid of a Speedivac vacuum pump. Chamber pressure rise during injection was recorded with a Statham Instruments differential pressure transducer in conjunction with an X - Y plotter and the appropriate electrical networks. The pressure transducer was connected to the vacuum chamber via 3/8-inch stainless steel tubing and a 1/8-inch pipe connecter.

B. OPTICAL SYSTEM

A schematic diagram of the optical apparatus used for light transmission measurements is shown in Figure 6. Two common laboratory white light sources were used for this experiment. Since photomultiplier tubes are too sensitive for direct exposure to bright light, even after having passed through high droplet concentrations, a series of

Kodak Wratten Gelatin neutral density filters were used to reduce the incident light intensity to an acceptable level.

Solution of Equation (6) for mean droplet diameter and droplet concentration requires that the transmittance be measured for two widely separated wavelengths of light. Hence, Thin Film interference filters of λ = 6328 Å, 5145 Å, and 4880 Å were employed in pairs to produce a high degree of spectral purity at these wavelengths. In order to prevent light of wavelengths other than those of the interference filters from affecting intensity measurements, the remainder of the system, up to the photomultiplier tube, was shielded to keep stray light out. A beam splitter was oriented so as to superimpose the two spectrally pure wavelengths along a common path through the test chamber. Intensity measurements for either of the two individual wavelengths were made by alternately chopping off the light from the other source.

A single photomultiplier tube was used to convert the transmitted light intensity to a measurable quantity of electrical current. A brief explanation of photomultiplier tube operation follows. Radiation incident on the photoactive grid within the envelope of the tube will release some electrons from that grid. A voltage drop then accelerates the electrons to the first of several plates where each electron in turn creates another cascade of electrons. This process continues, the current being amplified by as much as 10^6 times, until the electrons are led from the

photomultiplier tube to the photometer in the form of electrical current. This current is a direct measure of incident light intensity. Reference [7] contains more information on the construction and operation of photomultiplier tubes. An RCA 1P28 photomultiplier tube was used in this investigation because it possessed high spectral response for all wavelengths of light used.

The photometer was of central importance in this system since it ultimately provided the data necessary to determine the mean size and concentration of the droplets in question. A Pacific Photometric Model 11 Laboratory Photometer was used, which is designed for use with all side-window photomultiplier tubes and most head-on tubes having diameters of up to 2 inches. The Model 11 has a high-voltage control that allows the input voltage to be varied from -500 VDC to -1500 VDC, a nine-position measuring circuit covers full-scale ranges from 10 microamperes to 1 nanoampere, and a recorder output of 100 millivolts for all full-scale ranges is located on the back to the instrument. An X - Y plotter was connected to the photometer via this output jack and provided permanent records of the transmitted light intensities measured.

IV. EXPERIMENTAL TECHNIQUE

Numerous preliminary tests were performed, both with the liquid injection system and the optical apparatus, before the final experimental procedures were established. Initial liquid injection trials were performed with water. The small quantities of water vapor produced in the vacuum chamber made it mandatory to switch to another liquid with a much higher vapor pressure. Common laboratory acetone (see properties in Table I) was chosen and was used throughout the investigation. It was also quickly determined that injection orifices on the order of 0.01 inches in diameter would produce flow rates great enough to effect a measureable light attenuation, but low enough to restrict the pressure rise in the vacuum chamber to a reasonable rate. Final data was taken using injection orifices of 0.006, 0.010, and 0.0135 inches diameter.

Initial attempts to determine the droplet sizes in aerosols of acetone involved recording the light transmission, I/I_o, for two wavelengths of light along a common path through the aerosol. Such measurements would allow Equation (6) to be solved for mean droplet diameter and the volume concentration. However, all three of the wavelength filters which were used (6328 Å, 5145 Å, 4880 Å) produced the same intensity ratios, implying that the size number $\alpha = \pi D/\lambda$ was much greater than unity, i.e., the diameter of the droplets was much larger than the light

wavelength. Physically this meant that the droplet sizes were of such a magnitude that the photomultiplier tube was seeing their simple shadows for incident wavelengths within the visible spectrum rather than a diffraction pattern that is a strong function of wavelength, as in the case when α is of order unity.

Since the apparatus necessary for generating electromagnetic wavelengths outside the visible spectrum was not readily at hand, an independent method for evaluating the volume concentration, C_v, was used. If C_v could be determined, Equation (6) could be solved for D_{32} on the basis of a transmittance ratio for only one wavelength of light.

The volume concentration at some point in the spray cone is equal to the ratio of the lateral cross-sectional area of the spray cone at that point (provided the evaporation rate of a droplet is small compared to the time required for the droplet to travel from the injection orifice to the point of interest - see Discussion). Or, more simply, the volume concentration is equal to the ratio of the square of the orifice diameter to the square of the spray cone diameter at the point of interest. Polaroid photographs were taken of the spray cone, illuminated by a laser beam, for various experimental parameters and the dimensions of the cone were taken from the photographs. The cone dimensions so obtained were in close agreement with values reported by Schmidt [15] for similar experimental parameters.

Once the dimensions necessary for evaluating the volume concentration had been established, final light transmission measurements were made at three individual wavelengths for three different injection orifices at driving pressures of 50, 100, and 200 psig. The measurements were made in a plane 7 inches above the injection orifice.

Figure 9 shows typical chamber pressure rise curves for three driving pressures. Similar curves were obtained for the three injection orifice sizes used. From these pressure rise curves the flow rates for each nozzle were evaluated using the ideal gas law. Table III lists these injection flow rates for driving pressures of 50, 100, and 200 psig.

V. RESULTS

The final experimental technique employed to gain the information necessary to evaluate Equation (6) for D_{32} involved making light transmission measurements for three wavelengths of incident light (λ = 6328 Å, 5145 Å, and 4880 Å) through sprays of acetone injected through three nozzle orifices (d_o = 0.006", 0.010", and 0.0135") at three driving pressures (P_d = 50 psig, 100 psig, and 200 psig). Initial vacuum chamber pressure for all trials was taken as 0.00 psig. The numerical results of these measurements are tabulated in Table II.

The optical path length through the spray cone, at a height of 7 inches above the injection orifice where the light transmission measurements were made, was determined to be 2.74 inches for the condition under which light transmission ratios were evaluated. Early verification that the size number was much greater than unity for all wavelengths and droplet sizes allowed the mean scattering coefficient to be set equal to 2 for all calculations of D_{32}, thus removing the wavelength dependency of Equation (6). Mean droplet diameters calculated using these parameters spanned a range from 0.8 mils (d_o = 0.006", P_d = 200 psi) to 3 mils (d_o = 0.0135", P_d = 50 psi) as shown in Table II. These values are of the same order of magnitude as droplet diameters reported by Gooderum and Bushnell [8] for superheated waterjets.

Figure 8 is a graphical display of mean droplet diameter, normalized by injection orifice diameter, as a function of driving pressure and injection orifice diameter. Trends of the data points imply decreasing droplet diameter for decreasing injection orifice diameter and increasing driving pressure.

Typical vacuum chamber pressure rise curves for different driving pressures are shown in Figure 9. It is seen that the rate of pressure rise was constant during injection. Upon termination of injection the chamber pressure assumed a constant value after all of the liquid acetone in the vacuum chamber vaporized. Mass and volume flow rates based on such curves are tabulated in Table III.

VI. DISCUSSION OF RESULTS

A high degree of confidence can be afforded the light transmission method of particle size determination. Phelps [14] performed light transmission particle size analysis on various size-groups of graphite particles whose sizes had been predetermined by microscopic inspection. The graphite particles used were of the same order of size as the droplets observed in this study. The theorized mean particle sizes predicted by the light transmission theory were found by Phelps to be within 0.2 per cent of the sizes measured microscopically. Hence, this theory can be used to give an accurate measure of mean particle diameter, D_{32}.

The most likely source of error in the calculations of droplet diameter in this paper is the value of the optical path length, or the diameter of the spray cone at the instant the light transmission ratio was evaluated. The diameter of the spray cone that forms when liquid injection is initiated into a low-pressure chamber constantly decreases as the pressure rises in the chamber until a liquid stream forms as the chamber pressure surpasses the vapor pressure of the liquid. Hence, in this investigation the optical path length, for a given set of experimental parameters, was a function of the instantaneous vacuum chamber pressure at the time the light transmission ratio was evaluated. By coupled use of the time scales on the pressure rise curves and the light transmission plots, all

calculations of droplet size were made for the same instantaneous chamber pressure, 0.125 psia, and therefore the same optical path length. The dimensions of the spray cones were taken from photographs and were in close agreement with results reported by Schmidt [15]. However, in spite of the above technique the confidence placed upon the optical path length so obtained must be less than for the other experimentally measured parameters. An error for this parameter on the order of 15 per cent is possible.

The mass and volume flow rates tabulated in Table III were calculated using ideal gas law relations and values of pressure rise in the vacuum chamber taken from curves similar to those shown in Figure 9. These calculations will be discussed here in detail.

The constant rate of pressure rise in the vacuum chamber upon initiating injection is due to evaporation of the liquid droplets as they rise in the vacuum. The constant rate of pressure rise therefore implies a constant rate of liquid mass evaporation as long as injection continues and chamber pressure remains below the vapor pressure of acetone. Upon terminating injection the chamber pressure continues to rise for a short time at a steadily decreasing rate as the liquid mass left in the chamber at the instant the valve was closed vaporizes. When all the mass in the chamber has vaporized, the chamber pressure assumes a steady value.

What is not immediately obvious is that the volume of liquid in the tubing between the main valve and the injection orifice (a volume of 0.512 cubic inches) does not effect a measurable pressure change in the chamber for an extended period of time following termination of injection. When the main valve is closed, flash vaporization of only a small amount of liquid at the injection orifice reduces the liquid volume upstream of the orifice to the vapor pressure of acetone. The acetone vapor formed at the surface of the liquid then diffuses into the vacuum chamber through the injection orifice due to a driving pressure of about 3.5 psia. Calculations show that sonic flow of acetone vapor through the 0.010 inch diameter nozzle into the vacuum chamber will cause a pressure rise rate of about 4×10^{-4} psi per second, which is negligible compared to the relatively short time periods during which pressure rise curves were plotted.

In light of the above discussion, the stable pressure attained in the vacuum chamber following the termination of injection was due to the vaporization of the liquid mass that flowed through the injection orifice in the time span that the main valve was open, and so was used to calculate the ideal mass and volume flow rates. Primed values of mass and volume flow rates listed in Table III are those flow rates which would produce the constant rates of pressure rise actually observed, assuming flash vaporization of the injected liquid.

Calculation of the volume concentration at the point in the spray cone where the light transmission measurements were made assumed that a volume of liquid experienced negligible evaporation as it traveled through the spray cone. As a check on this assumption, calculations were made to estimate how much liquid volume was lost to vapor in the 6.5×10^{-3} seconds required for a drop to traverse the 7 inches from the injection orifice to the point where the light transmission measurements were made. These calculations showed that $\Delta D/D$ was of the order of 10^{-4}, or that a negligible volume of liquid vaporized during the time span in question. Thus, the volume concentration was evaluated as the ratio of the square of the injection orifice diameter to the square of the diameter of the spray cone at a distance of 7 inches above the injection orifice.

VII. SUGGESTIONS FOR FURTHER INVESTIGATION

The light transmission theory used in this study provides a flexible method for investigation of droplet sizes and concentrations in aerosols, fogs, and sprays. Current ideas for future investigation include:

a) Make droplet size measurements as a function of distance from the injection orifice to determine how the droplet sizes vary as the spray fans out.

b) Incorporate a heat exchanger into the liquid injection system and investigate the temperature dependence of the droplet sizes.

c) Conduct droplet size experiments with a number of different liquids with a wide range of vapor pressures and viscosities to determine the effect of these parameters on droplet sizes.

d) Use data similar to that obtained in this study to develop a theory for predicting droplet sizes under a variety of environmental conditions.

TABLE I

PHYSICAL AND THERMODYNAMIC PROPERTIES OF ACETONE

Chemical names	Dimethyl Ketone, 2-propanone
Molecular formula	CH_3COCH_3
Formula weight	58.079
Melting point	- 138.28° F
Boiling point	132.98° F at 1 std. atm.
Vapor pressure	3.487 psia at 68° F
Density	0.0285 lb/in^3 at 68° F
Viscosity	0.124 in/sec at 77° F
Index of refraction	1.3588
Ratio of specific heats (C_p/C_v)	1.099

TABLE II

ACETONE DROPLET SIZE MEASUREMENTS

d_o (inches)	P_d (psig)	I/I_o			Average I/I_o	-Ln (Ave I/I_o)	D_{32}/d_o
		λ=6328Å	λ=5145Å	λ=4880Å			
0.006	50	.973	.964	.969	.969	.0319	.206
	100	.956	.971		.965	.0356	.184
	200	.960	.950		.955	.0464	.142
0.010	50	.954	.959	.948	.956	.0447	.245
	100	.947	.969		.955	.0465	.236
	200	.918	.906		.912	.0922	.119
0.135	50	.941	.946	.933	.943	.0584	.253
	100	.939	.951		.941	.0610	.242
	200	.907	.887		.897	.109	.136

TABLE III

MASS AND VOLUME FLOW RATES

d_o (inches)	P_d psig	t_{open} (sec)	$\Delta\dot{P}$ psia/sec	ΔP_{total} psia	$\dot{M}'$ lb/sec	$\dot{V}'$ in^3/sec	$\dot{M}_{ideal}$ lb/sec	$\dot{V}_{ideal}$ in^3/sec
	50	20.0	.0165	.425	.000295	.0103	.000379	.0133
0.006	100	18.5	.0358	.762	.000639	.0224	.000723	.0257
	200	15.0	.0469	.804	.000835	.0293	.000955	.0335
	50	7.0	.0753	.647	.00134	.0471	.00165	.0578
0.010	100	6.3	.101	.756	.00180	.0632	.00214	.0750
	200	5.5	.135	.863	.00240	.0842	.00280	.0981
	50	2.5	.212	.671	.00379	.133	.00478	.168
0.0135	100	2.2	.285	.767	.00508	.178	.00621	.218
	200	1.8	.385	.833	.00686	.241	.00825	.289

FIGURE 1. APPARATUS FOR THE STUDY OF LIQUID STREAMS INJECTED INTO A LOW-PRESSURE CHAMBER

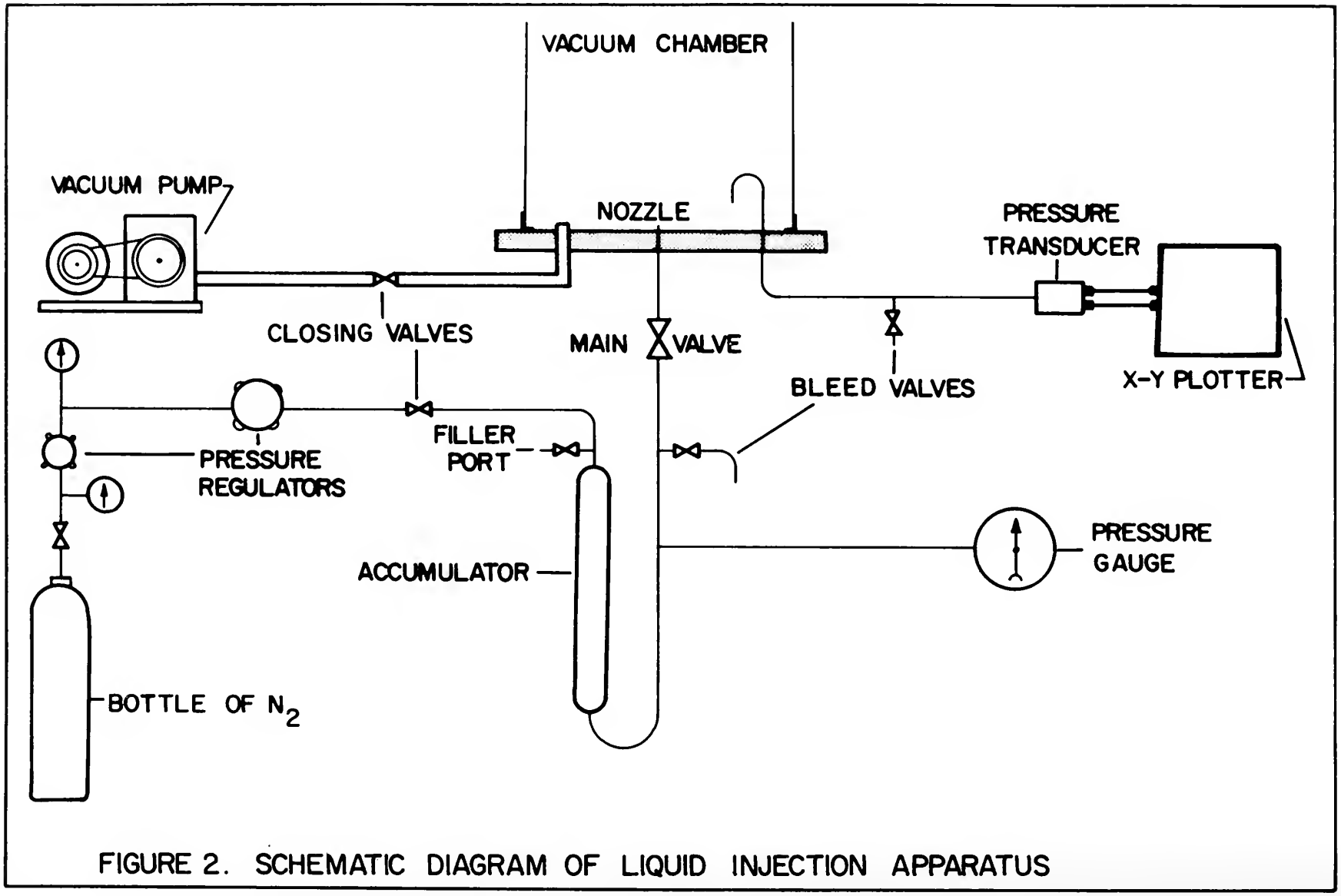

FIGURE 2. SCHEMATIC DIAGRAM OF LIQUID INJECTION APPARATUS

FIGURE 3. COMPONENTS OF NOZZLE ASSEMBLY

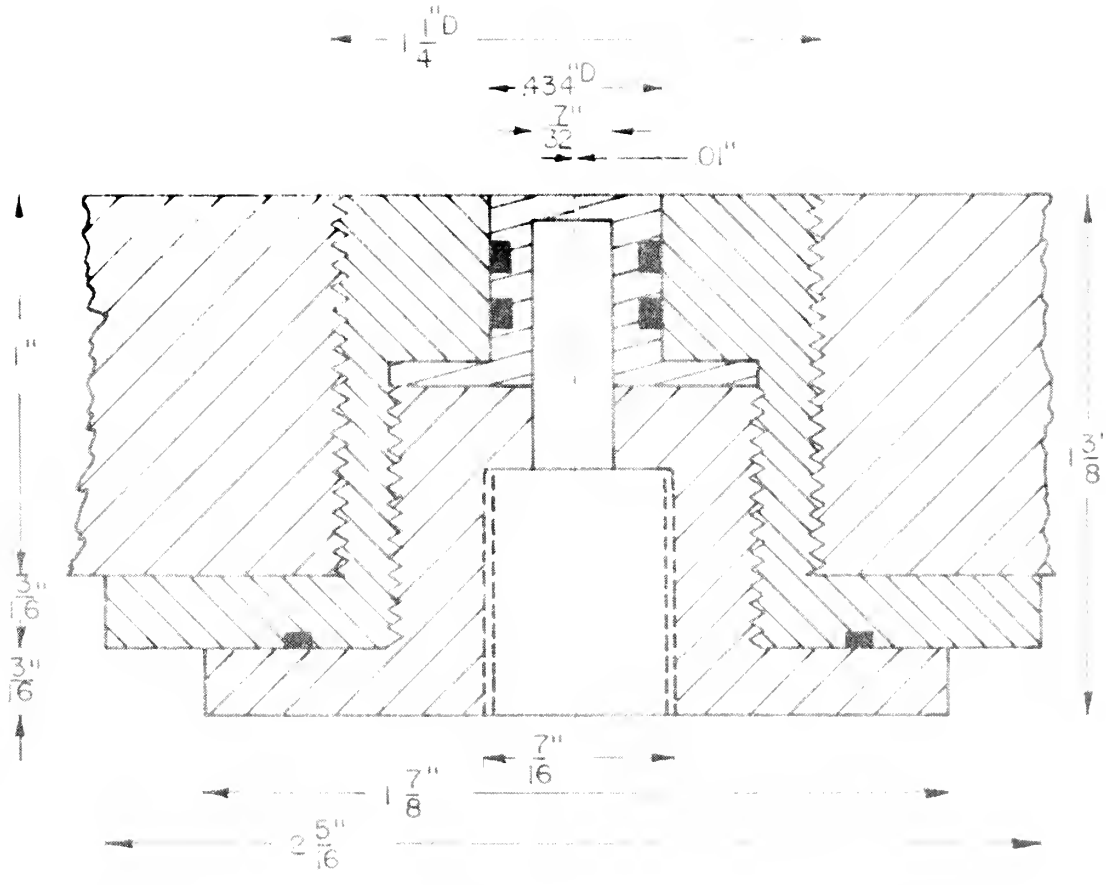

FIGURE 4. CROSS-SECTION OF NOZZLE ASSEMBLY

FIGURE 5. ACETONE SPRAY PRODUCED BY d = 0.006", P_d = 100 psig

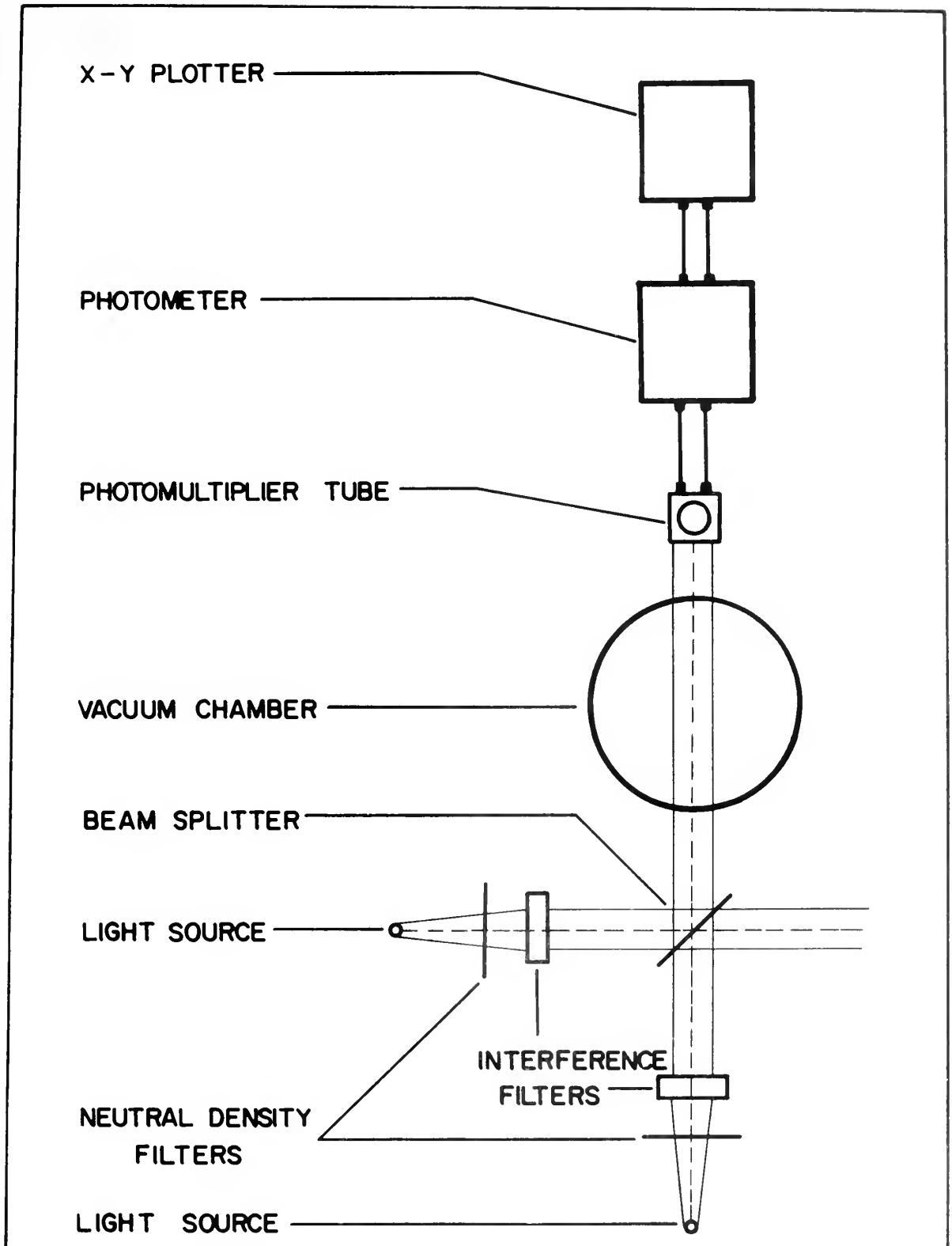

FIGURE 6. OPTICAL APPARATUS USED FOR LIGHT TRANSMISSION MEASUREMENTS

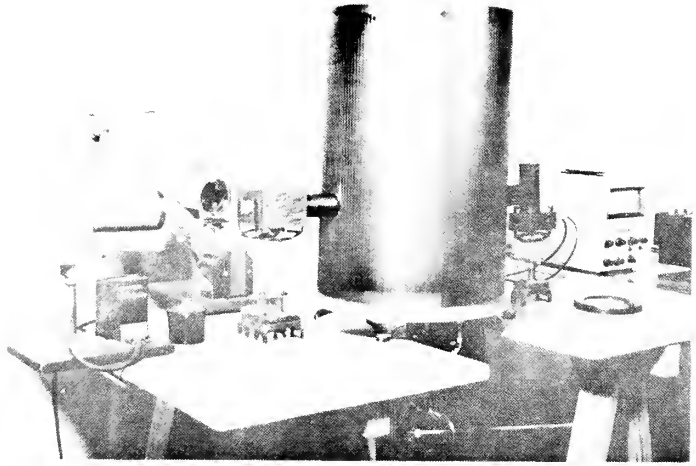

FIGURE 7. OPTICAL APPARATUS IN OPERATION

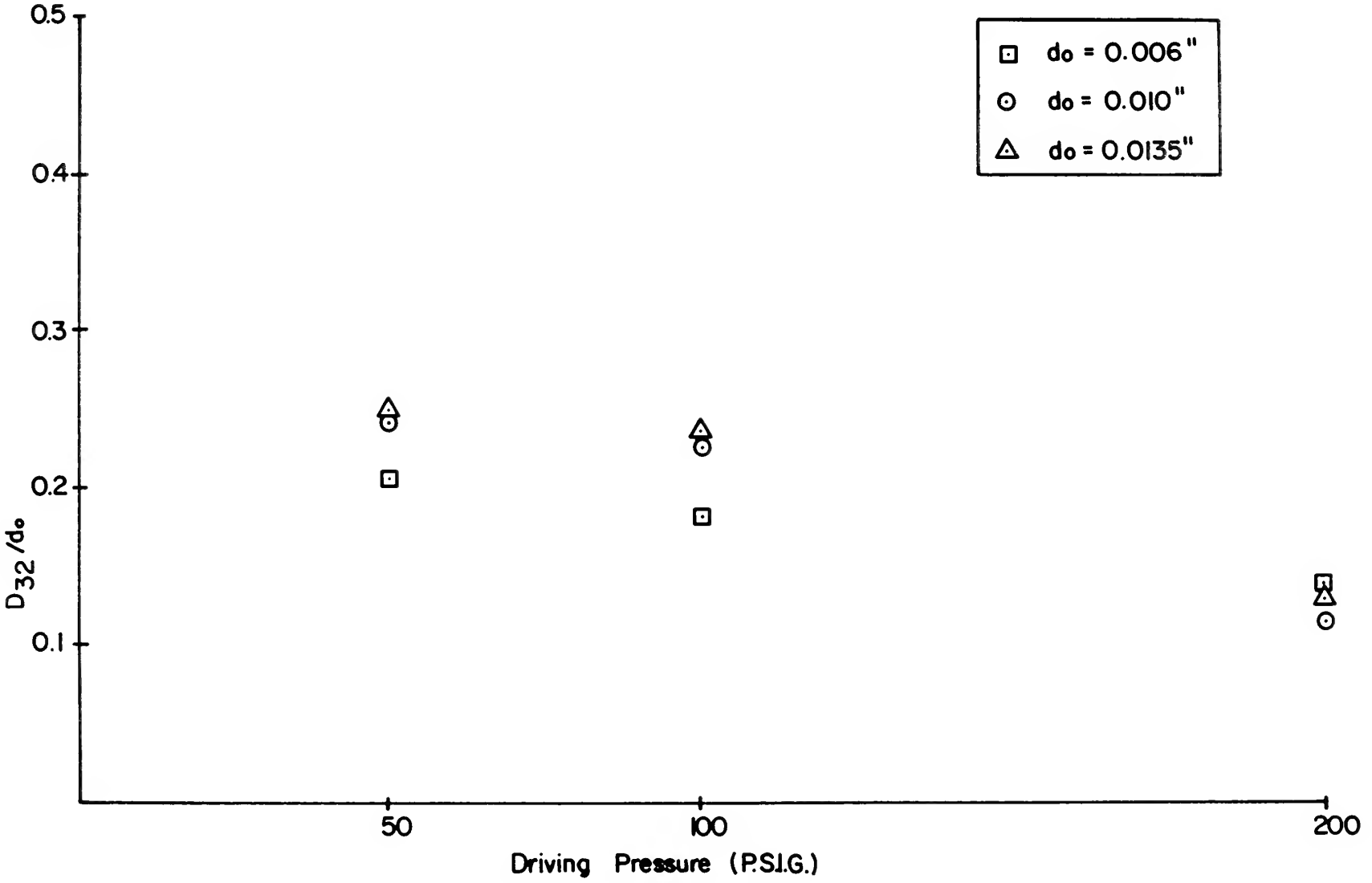

FIGURE 8. D_{32}/d_o VS. DRIVING PRESSURE

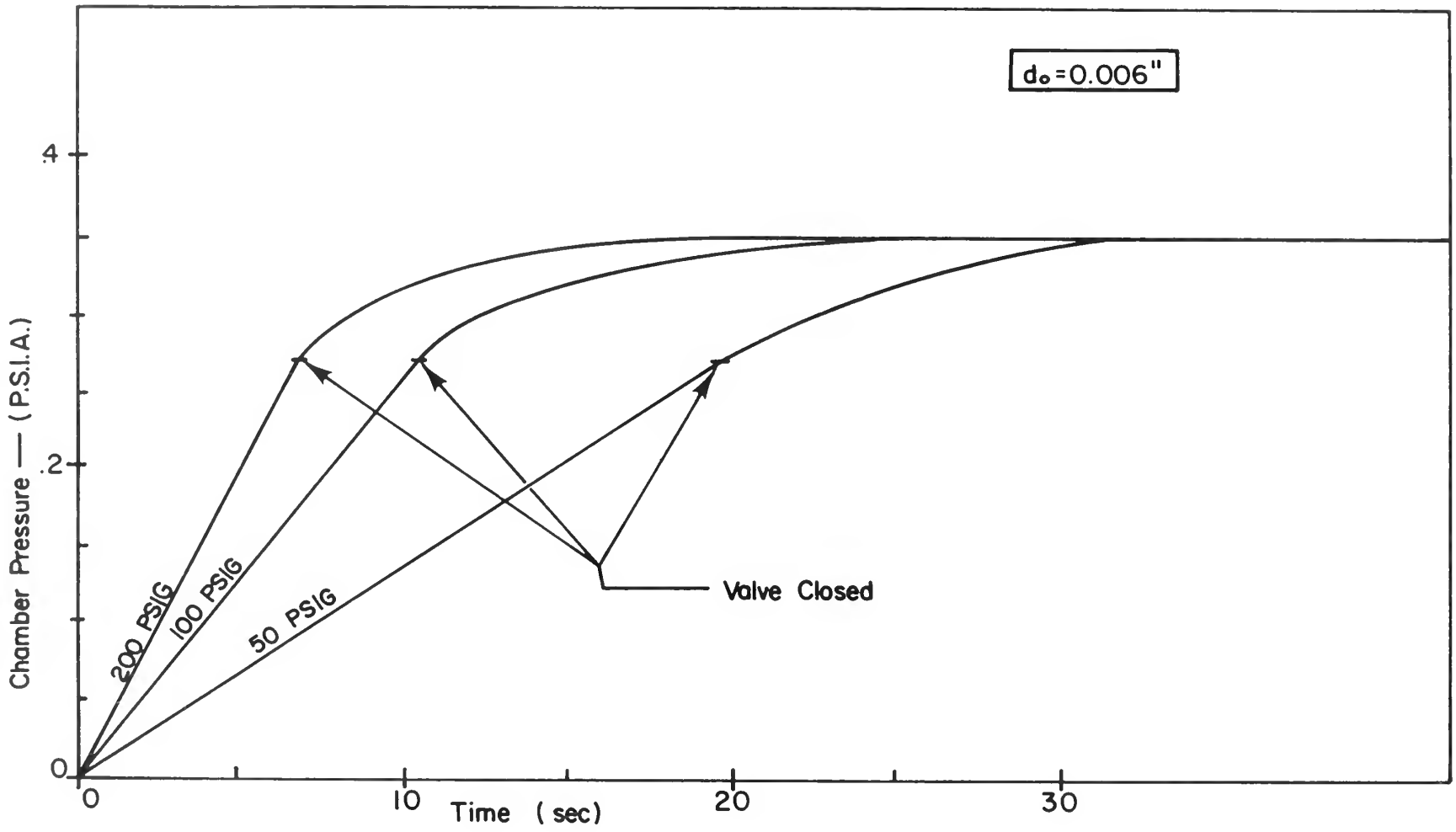

FIGURE 9. INCREASE IN CHAMBER PRESSURE VS. TIME FOR VARIOUS DRIVING PRESSURES

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13. ABSTRACT

An apparatus was constructed for optical investigation of the sprays produced by liquid injection into a vacuum using various nozzle orifice sizes and driving pressures. A light transmission technique was employed to measure the mean diameter of the droplets in acetone sprays. Independent calculation of the densities of the sprays allowed the droplet sizes to be established by measuring the optical transmittance of a single spectrally pure wavelength of light through the sprays. A graph of droplet diameter, normalized for nozzle orifice diameter, vs. driving pressure was constructed. Mass and volume flow rates for the liquid injection system were calculated.

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